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Generation of ultra-narrow, stable and tunable millimeter- and terahertz- waves with very low phase noise

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OCIS codes: (290.5900) Scattering, stimulated Brillouin; (350.4010) Microwaves; (060.5625) Radio frequency photonics.

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1. Introduction

Waves in the millimeter (30 - 300 GHz) and Terahertz (0.3 - 3 THz) region of the electromagnetic spectrum have drawn much interest in recent years for several applications. They are particularly attractive for molecular fingerprint spectroscopy, since rotational excitations in many molecules of interest such as drugs, explosives and poisonous contamination fall within the THz region of the spectrum [1–3]. Additionally, THz waves are important for quantum coherence experiments [4], and are instrumental in radio-astronomy [5]. In the field of communications, millimeter- and terahertz-waves theoretically enable the wireless transmission of data at rates of up to several Tbit/s, over outdoor links and within data centers. Such data rates would be orders of magnitude higher than those offered by current wireless systems which employ lower-frequency carriers [6].

All of the above applications require stable, and often tunable, sources of continuous-wave (CW) THz-frequency radiation, having a narrow linewidth and low phase noise. In ultra-high-bitrate wireless links, for example, the usable modulation format and therefore the spectral efficiency depends on the linewidth and phase noise of the carrier. Thus, the quality of the generated wave defines the transmissible data rate. However, the generation of high-quality THz-waves is technologically challenging, and is currently restricting many of their potential applications [5]. CW-THz waves can be generated through electronic up-conversion of radio and microwave-frequency tones [7, 8]. Nevertheless, the noise associated with electronic up-conversion scales quadratically with the harmonic frequency-multiplication order [9], whereas the power decreases. High-frequency, GaAs-based integrated electronic circuits are available for the generation of sub-millimeter-wave radiation [10]. However, their tuning range is restricted to tens of GHz due to the bandwidth of the electrical mixers. Quantum cascade lasers (QCLs) are promising sources for generating radiation at the higher end of the THz spec-

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trum [11–14]. Frequency tuning of QCLs is possible through refractive index variations and heating, however it is limited to variations of 5 GHz only [15]. QCLs working at room temperature are rather limited to a wavelength range of 3-5 μm [16]. However, broadband THz-QCLs for longer wavelengths require operation at cryogenic temperatures, which complicates their practical use.

Systems based on electro-optical down conversion of two optical waves mixed together can produce millimeter-wave and THz tones of a very high quality. However, the scheme requires that the two optical waves are locked together in both frequency and phase. In principle, two independent CW laser sources can be phase-locked to a frequency comb generated by a Ti:Sapphire laser [17] or a mode-locked fiber laser [18]. The linewidth of the generated signal mainly depends on that of the used laser sources. Linewidths on the order of 1 MHz were obtained using single-frequency CW laser sources [19, 20]. Much narrower linewidths in the range of 150 kHz [18] and even 2 Hz [17] were achieved using external cavity lasers. The phase noise of the generated waves was between -50 to -70 dBc/Hz at an offset of 10 kHz. Such systems are implemented in a free-space setup for the purpose of spectroscopy [21]. However the phase locking of a CW laser to the comb involves high-precision phase-locked loops, and is therefore rather complex. In [19] and [20] for instance two independent frequency combs are separately phase-locked to a microwave reference synthesized from a hydrogen maser linked to coordinated universal time.

An elegant way to overcome these restrictions is to use two intrinsically correlated optical fields to generate a signal at the desired difference frequency. A number of such spectral tones can be produced by the generation of higher harmonics due to phase or intensity modulation [22–26] or a pumped fiber loop [27]. Conventional optical filters are then used to select two particular lines. Several measurements reported linewidths of 4 Hz and a phase noise of -75 dBc/Hz @ 100 Hz [22]. The maximum frequency is restricted however by the bandwidth of the modulators. In addition, a high-quality microwave source is required for the initial modulation.

The spectral components of passively mode-locked femtosecond lasers are excellent candidates for electro-optic down conversion and the generation of THz waves. The precision provided by high-quality frequency-comb sources revolutionized the metrology of fundamental physical constants [28–31]. Mode-locked, erbium-doped fiber lasers, for example, are low-cost, robust and readily available. They generate a comb of frequencies that spans several THz, and can be broadened further to a super-continuum of more than an octave through propagation in nonlinear media. The width of each comb line is below 1 Hz, even without external stabilization. This inherently narrow linewidth suggests that extremely narrow-band THz waves might be generated through electro-optic down-conversion processes. However, direct interference between two lines of such high-quality frequency-comb source has not yet been employed for the generation of mm-wave and THz radiation. The spectral separation between comb lines, which is on the order of tens of MHz, is far too narrow for the selection of only two tones with standard optical filters.

In this work, the very high accuracy of such a frequency comb is directly transferred to the millimeter-wave and THz domain. Contrary to setups where very high harmonics of the repetition rate of mode-locked pulsed lasers were used, in which the noise grows and the power decreases with the harmonic order, here two lines of the comb are selected and superposed directly. Since conventional optical filters are not available for this purpose, we utilize the polarimetric attributes of stimulated Brillouin scattering (SBS) in standard, weakly birefringent fibers to arbitrarily select and amplify two tones out of the frequency comb, obtained from a supercontinuum generated in a highly nonlinear fiber, while all other spectral components are effectively suppressed through polarization discrimination. The amplification is carried out us-

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ing two tunable distributed feedback (DFB) laser diodes which serve as Brillouin pumps. The SBS pumps are locked to the specific modes via the Pound-Drever-Hall technique [32]. The selection of tones separated by as much as 5 THz is demonstrated, though the physical limit to the difference frequency is set only by the spectral width of the supercontinuum. The two tones are then mixed together on a broadband photodiode to obtain extremely stable down-converted CW radiation where the maximum achievable THz frequency depends on the bandwidth of the photo mixer. The proposed method is simple and reliable and it requires only a light-weight fiber laser source and standard fiber-optic components.

In this paper the following is presented a) the electrical characterization of the generated waves, limited by the bandwidth of the electrical equipment to 110 GHz, showing a linewidth of 1 Hz and phase noise of -105 dBc/Hz @ 10 kHz; b) the generation and transmission of a 200 GHz and a 1 THz wave over a distance of 24.5 cm; c) the modulation of the wave with a 40 Gbps pseudo-random bit sequence (PRBS).

2. Frequency comb

The basis of the electro-optic down-conversion is the heterodyne beating of two optical waves on an appropriate photo mixer. The photo mixer is a nonlinear element, such as a photodiode [33], which down-converts the incoming beat signal from the optical into the electrical domain. The photocurrent at the detector output is proportional to the combined intensity of the two optical fields added together. Let us denote the amplitudes of the two optical waves as $A_{1,2}(t)$, where t represents time, and their frequencies and phases by $f_{1,2}(t)$ and $\varphi_{1,2}(t)$, respectively. In addition to base-band terms which stem from the individual intensities of the two waves, the instantaneous photocurrent also includes a beating term:

$$i_{out} \sim A(t) cos[2\pi\Delta f(t) + \varphi(t)] \tag{1}$$

where $A(t) = A_1(t)A_2(t)$, $\Delta f(t) = f_1(t) - f_2(t)$ and $\varphi(t) = \varphi_1(t) - \varphi_2(t)$. The photocurrent therefore oscillates at the difference frequency Δf, provided that the photo mixer bandwidth exceeds that frequency. The difference frequency can reach well into the millimeter-wave or even THz spectral regions [34].

If the two waves were completely independent of each other, the output signal would exhibit amplitude, frequency and phase noise. The generation of a high-quality, CW millimeter- or terahertz-signal requires that both optical waves are correlated, i.e. the amplitudes are stable, the difference between their central frequencies is fixed, and the difference between their phases is stable. Individual spectral lines extracted from the output of a mode-locked, ultra-short pulsed laser meet the necessary requirements. The frequency separation between the lines is only defined by the repetition rate of the laser, which can be stabilized very precisely. Additionally, a fixed phase relationship prevails across the entire spectrum. The amplitudes of the lines are governed by the shape of the pulse, and can be very stable as well. The bandwidth can be further extended using self-phase modulation and four-wave mixing processes along fiber sections, if necessary. Figure 1 shows the power spectral density (PSD) of the supercontinuum generated by the mode-locked pulsed fiber laser, as explained in the experimental part. The measurements were acquired using both a standard optical spectrum analyzer (OSA) and a high-resolution OSA with 10 MHz resolution [35, 36]. The PSD consists of discrete tones that are separated by 75 MHz and span a bandwidth of 100 THz.

3. Frequency extraction

Efficient millimeter-wave and terahertz generation requires that only two spectral lines of the ultra-short pulsed laser spectrum are selected, while all other components are strongly suppressed. The presence of residual fields at additional frequencies would manifest itself as noise.

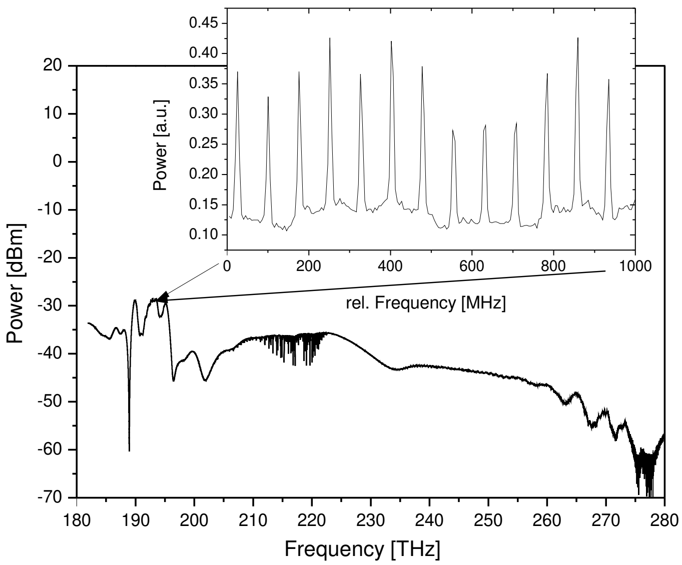

Fig. 1. Spectrum of the used frequency comb measured with a conventional OSA. The ps-laser generates pulses with a repetition rate of 75.4 MHz. These pulses are spectrally broadened in a nonlinear fiber and can afterwards be compressed to fs-pulses. Here this feature is not required. The inset shows a 1 GHz wide part of the spectrum measured with a high resolution OSA [38].

Such spectral selectivity is highly challenging, since conventional optical band-pass filters cannot discriminate between tones that are separated by only 75 MHz. We therefore employ narrow-band SBS amplification of the two spectral components of interest.

In SBS, a relatively intense pump wave interacts with a counter-propagating, typically weaker signal wave, which is detuned in frequency [37]. The combination of the two waves generates a slowly traveling intensity beating pattern, whose frequency equals the difference between the optical frequencies of the pump and signal waves. Through electrostriction, the intensity wave introduces traveling density variations, or an acoustic wave, which in turn leads to a traveling grating of refractive index variations, due to the photo-elastic effect. The traveling grating can couple optical power between the counter-propagating pump and signal waves. Efficient coupling, however, requires that the difference between the two optical frequencies should closely match the Brillouin frequency shift $\nu_B \sim 11$ GHz, depending on the 1570 nm wavelength region used, the type of fiber as well as the strain and temperature of the fiber. The amplification bandwidth achieved with CW pumping is rather narrow: on the order of 10-30 MHz, as decreed by the relatively long lifetime of acoustic phonons [37]. Significantly for our application, this bandwidth is narrower than the separation between neighboring lines in the frequency-comb spectrum. If the frequencies in the comb have a smaller spacing than 10 MHz, the bandwidth of the SBS can be reduced [39, 40].

Further suppression of unamplified spectral contents may be obtained based on polarization discrimination. SBS amplification over standard, weakly-birefringent fibers is highly polarization-dependent [41–44]. The process is associated with two orthogonal states of polarization (SOPs) of the amplified signal, corresponding to maximum and minimum gain. The two states are determined by the choice of input pump SOP [42–44]. Let us denote the unit Jones vectors of these two SOPs at the signal input end of the fiber as $\hat{e}_{max}^{in}$ and $\hat{e}_{min}^{in}$, and the corresponding vectors at the signal output end as $\hat{e}_{max}^{out}$ and $\hat{e}_{min}^{out}$, respectively. The maximum and minimum amplitude gain values are denoted as $G_{max}(\omega_s)$ and $G_{min}(\omega_s)$ respectively, with ω_s being the frequency of the signal. Consider an arbitrarily polarized input signal component:

$$\vec{E}_{in}(\omega_s) = E_0(\omega_s)\left(a\hat{e}^{in}_{max} + b\hat{e}^{in}_{min}\right) \tag{2}$$

where $E_0(\omega_s)$ is a scalar, frequency-dependent complex magnitude of the input waveform and $|a|^2 + |b|^2 = 1$. The corresponding output signal is given by [42–44]:

$$\vec{E}_{out}(\omega_s) = E_0(\omega_s)[aG_{max}(\omega_s)\hat{e}^{out}_{max} + bG_{min}(\omega_s)\hat{e}^{out}_{min}] \tag{3}$$

Since within the SBS bandwidth $G_{max}(\omega_s) \gg G_{min}(\omega_s)$, then unless a is vanishingly small, the output SOP of the Stokes wave is drawn towards $\hat{e}^{out}_{max}$. In contrast, for ω_s outside the Brillouin gain line $G_{max}(\omega_s) \approx G_{min}(\omega_s) \approx 1$. Therefore the output SOP of unamplified spectral components of the signal wave may differ substantially from that of the amplified components. Hence a carefully aligned output polarizer can further discriminate between the two spectral lines of interest and all other tones. Details of the polarization alignment procedure are given in [44].

4. Experimental setup

The experimental setup is depicted in Fig. 2. The frequency comb is obtained through a supercontinuum generation using a mode-locked fiber laser (Toptica FemtoFiber Pro SCIR; MLL) whose output PSD was shown in Fig. 1. The integrated output power of the supercontinuum is 23 dBm, distributed over more than an octave in the spectrum (980 nm – 2200 nm). The frequency comb enters a 5 km long AllWave®fiber which serves as a Brillouin gain medium, via polarization controller PC_1. Two Brillouin pump waves, generated by DFB laser diodes LD_1

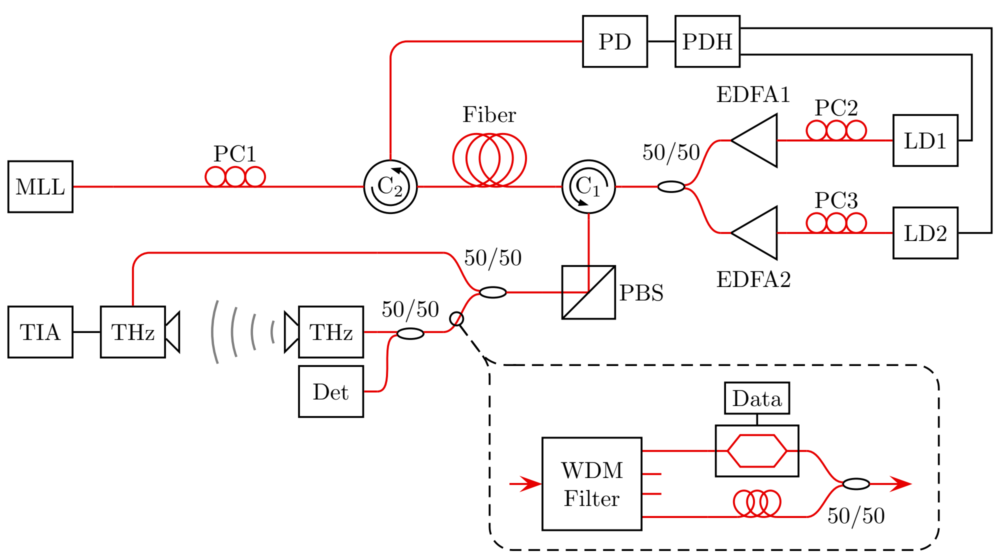

Fig. 2. Experimental setup. MLL: mode-locked laser, PC: polarization controller, PD: photo diode, PDH: Pound-Drever-Hall module, LD: distributed feedback laser diode, EDFA: erbium-doped fiber amplifier, PBS: polarization beam splitter, C: circulator, Det: measurement components including optical and electrical spectrum analyzer, TIA: transimpedance amplifier. The red lines correspond to optical and black lines to electrical links. The dashed box shows the setup for the modulation of the wave.

and LD_2 and amplified separately via erbium-doped fiber amplifiers (EDFA), are injected from the opposite into the SBS gain medium via a 3 dB coupler and circulator C_1. The SOP of the pump waves is controlled with the polarization controllers PC_2 and PC_3. The output power of both EDFAs is 21 dBm.

The frequency of each of the two DFB lasers is automatically adjusted to provide SBS amplification of a particular comb line with help of Pound-Drever-Hall (PDH) modules [32]. In general, a PDH module serves to lock a diode laser to the maximum of an absorption or transmission peak of a reference medium (e.g. an optical resonator). Therefore, the light from the laser to be stabilized is phase-modulated, and the reflection by the resonator is measured using a fast photo detector. The modulation frequency is predetermined by a local oscillator inside the PDH module. The electronic signal from the detector is mixed with the local oscillator signals, and low-pass-filtered. The resultant signal (the error signal) is essentially the derivative of the transfer function of the resonator and represents the deviation of the laser frequency from the actual resonance frequency of the optical resonator. The generated PDH error signal is used to regulate the laser current. In the specific experiment the PDH-modules utilize the depletion of the pump waves for the control of the laser current of LD_1 and LD_2. If the signal is amplified, the power of the pump wave is transferred to the signal and the power of the pump wave itself decreases. The PDH stabilizes the LDs to the minimum power of the pump and therefore to the maximum amplification for the counter-propagating signal.

The laser diodes are directly modulated at a reference frequency and the pump waves are coupled out with the help of the circulator C_2. The two amplified comb lines are coupled out of the fiber via C_1, pass through a polarization beam splitter (PBS) and are split by a 3 dB coupler between a THz transmitter and receiver. Before the transmitter the signal is split again with a 3 dB coupler to the detection and analysis branch (Det). This detection consists of a broadband photo diode, as well as an optical (OSA) and electrical (ESA) spectrum analyzer. For the electrical characterization of the generated millimeter- and terahertz-waves we used a photodiode with a 3-dB bandwidth of 100 GHz and electrical mixers. Electrical spectral analysis was possible up to a frequency of 110 GHz. Wireless transmission of millimeter- and terahertz-waves was demonstrated by using a commercially available THz-spectroscopy setup with parabolic mirrors and photo mixers based on InGaAs on InP from Toptica [45]. The photo mixer modules operate at optical wavelengths around 1550 nm and are specified for the generation of frequencies up to 2 THz. However, there are different types of THz photo mixers that are capable to generate millimeter- and THz-waves up to frequencies above 5 THz, e.g. GaAs photo mixers operating around 850 nm [46]. The maximum optical input power for the THz transmitter is approx. 14 dBm [45]. This results in typical millimeter- and THz-wave transmission powers of 4 µW at 100 GHz and 0.5 µW at 500 GHz, respectively. However, with a different photo mixer, e.g. of uni-travelling carrier (UTC) design [33], higher transmission powers can be generated. For the down conversion of the signal, the receiving photo mixer requires both the THz wave and the beat note of the lasers, i.e. the same optical tones that drive the transmitter. These two signals are down-converted, or mixed, to a DC photocurrent. The received signal is measured with a transimpedance amplifier (TIA) and a lock-in amplifier. Therefore, the signal is modulated by chopping the transmitter bias voltage at a lock-in frequency of 7.6 kHz (not shown).

PC_2 and PC_3 were aligned so that the SOPs of both pump waves are the same. PC_1 was adjusted so that unamplified comb lines are blocked-off entirely by the PBS, whereas the two spectral lines of interest are partially transmitted [44], due to the SBS polarization pulling as discussed above.

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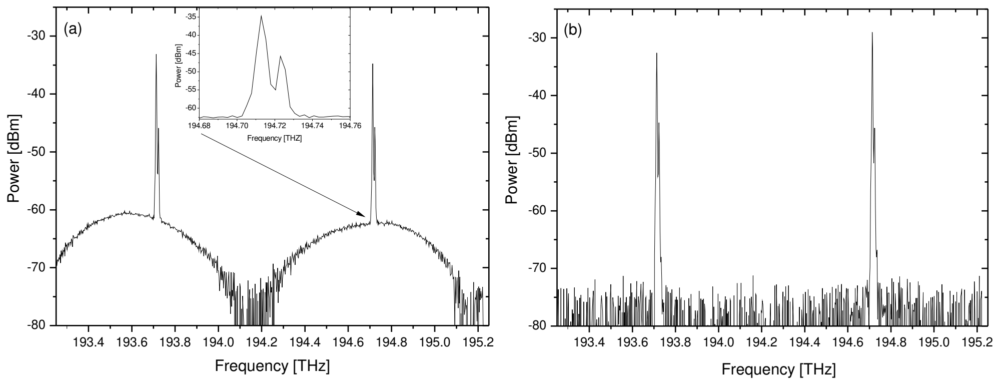

Fig. 3. Optical spectrum of two amplified comb modes with SBS (a) and with SBS supported by polarization pulling (b). The superposition of the two modes in an appropriate photo mixer would produce a signal with a frequency of around 1 THz (999.89 GHz). The inset shows the spectrum of one of the amplified modes with higher resolution.

5. Results

Figures 3(a) and 3(b) show the PSDs of the frequency comb following SBS amplification by the two pump waves, with and without the output PBS. Two spectral lines separated by 1 THz were selected in the particular example. The 13,261 spectral lines between the two chosen tones are rejected by more than 40 dB by the polarization-enhanced SBS process. The two additional peaks, around 10 dB lower than the amplified sideband and upshifted in frequency by around 11 GHz, are the Rayleigh backscattered pumpwaves. In Fig. 4 the output PSDs for tone spacings of 2 THz (red), 3 THz (black) and 5 THz (blue) are shown, respectively. The suppression of unamplified tones is somewhat degraded with increased frequency separation, due to polarization mode dispersion in the Brillouin gain medium.

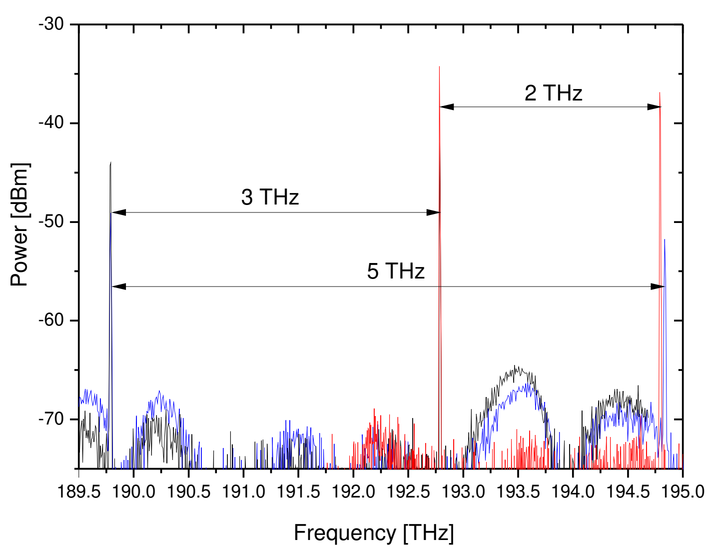

Fig. 4. Selective amplification of two comb tones using SBS and polarization pulling. The frequency spacing was 2 THz (red), 3 THz (black) and 5 THz (blue).

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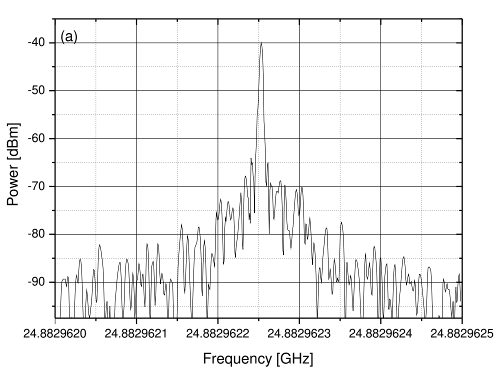
Figure 5(a) shows the electrical PSD of the beat signal that was generated by mixing two selected tones that are spaced by 24.882 GHz. In order to assist the initial suppression of many of the undesired comb tone, an additional optical prefilter (WS) was used at the output of the MLL. The prefilter provided two pass-bands, centered at the frequencies of the two chosen tones, each with a 3-dB bandwidth of 10 GHz. At the output of the WS, each of the two chosen modes is accompanied by around 130 additional tones, which are filtered by SBS and the associated polarization pulling. The FWHM linewidth of the generated mm-wave, directly measured with an ESA, was 1 Hz, limited by the resolution bandwidth of 1 Hz. However, it is supposed that the real linewidth is below 1 Hz. Phase noise measurements are shown in Fig. 5(b). The phase noise at a frequency offset of 10 kHz from the optically generated micro-wave carrier was -104 dBc/Hz. The obtained phase noise is several orders of magnitude lower than in the best reported results for setups were two external lasers were locked to two comb lines [17–21]. In our setup the two DFB lasers are locked to the comb lines by the PDH modules as well. Thus, for comparison we superimposed the two locked DFB-lasers at the output of C_2. The measured linewidth and phase noise was 3 MHz and -67 dBc/Hz @ 10 kHz, respectively. The down-conversion interference of the two DFBs results in noisier mm-waves due to their broader linewidths in the order of MHz and the independent phase of both sources. Thus, the linewidth is at least 6 orders of magnitude broader than that of Fig. 5, and the phase noise is 4 orders of magnitude larger.



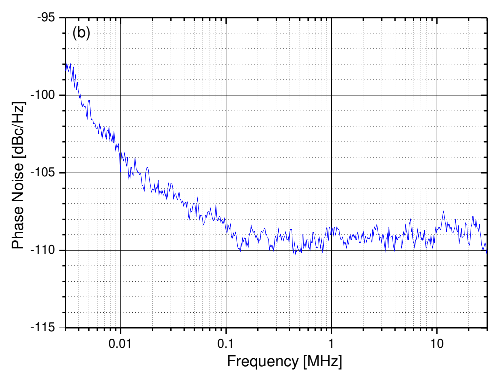


Fig. 5. Generated microwave signal with a frequency of 24.88296225 GHz. The measured linewidth was 1 Hz and limited by the resolution bandwidth of the electrical spectrum analyzer. In (b) the measured phase noise is shown.

The characterization of waveforms beyond 25 GHz required additional mixers at the electrical spectrum analyzer, resulting in a reduced resolution bandwidth of 300 Hz. Figures 6(a) and 6(b) show the PSD and phase noise measurement of a generated millimeter-wave at 110 GHz. The measured linewidth is 300 Hz, limited once again by the resolution bandwidth of the ESA when using an external mixer. Here too, the true linewidth of the generated mm-wave is likely much narrower. The phase noise was -101 dBc/Hz at 10 kHz offset, 3 dB lower than that of the 24 GHz signal. We relate this minor difference to the imperfections of our setup and the additional mixer.

The spectral characteristics as well as the phase noise of the generated waveforms above a frequency of 110 GHz cannot be measured directly using commercially available equipment, although reports are provided in the research literature [47]. In order to demonstrate the down-conversion mixing between two tones that are separated by more than 110 GHz, the wireless transmission link across a distance of 24.5 cm was manually interrupted by insertion of a metal

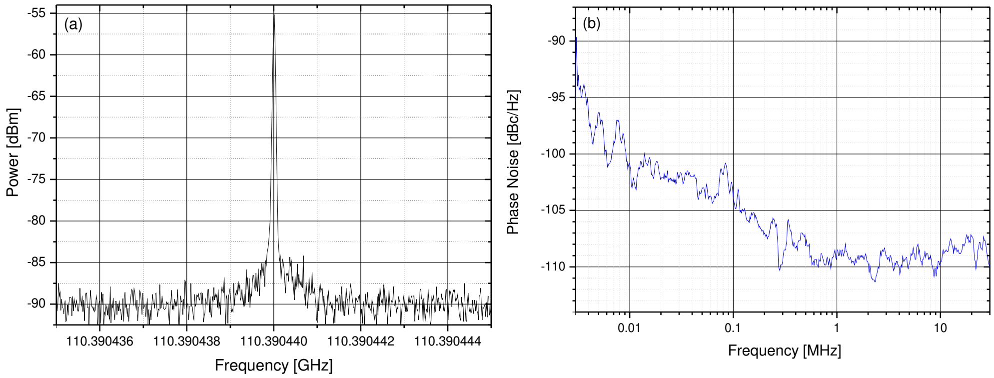


Fig. 6. (a) Generated millimeter-wave signal with a frequency of 110.39044 GHz. The measured linewidth was restricted by the resolution bandwidth of the ESA due to the used microwave mixers (<300 Hz). In (b) the phase noise measurement is shown.

plate. The THz-receiver produced a down-converted photocurrent which was zero for the interrupted beam, and non-zero during the transmission of generated THz- and millimeter-waves, as seen in Figs. 7(a) and 7(b). In the examples, the input to the transmitter photo-mixer consisted of two optical tones separated by 200 GHz and 1 THz, respectively.

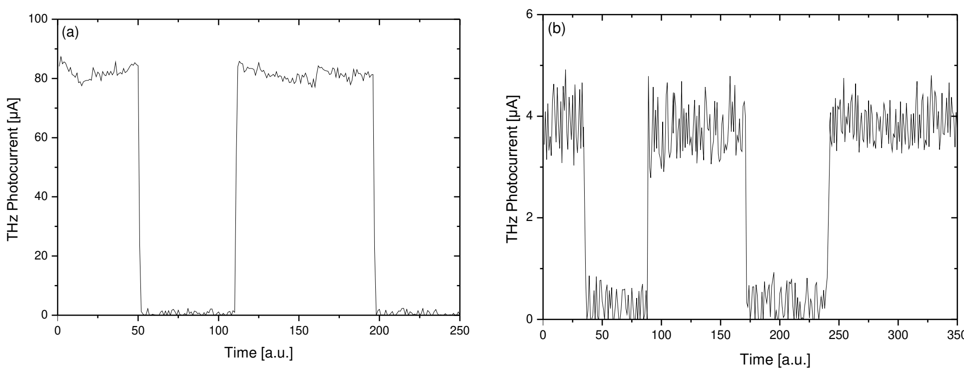


Fig. 7. Measured photocurrent at the THz-receiver for 200 GHz (a) and 1 THz (b). At the intervals with zero photocurrent, the free-space link was intentionally interrupted.

Lastly, we demonstrate the generation of modulated carriers. However, the modulated data could not be transmitted over free space due to the limited bandwidth of 10 kHz of the transimpedance amplifier used in the THz setup. For the generation of modulated carriers, the two 100 GHz-spaced tones are separated by a conventional wavelength division multiplexing (WDM) filter. The dashed box in Fig. 2 depicts the setup for the data modulation. One of the tones is modulated in a Mach-Zehnder modulator by a 40 Gbit/s pseudo random bit sequence from a pattern generator. The waves are then recombined, and an eye diagram is measured before the THz transmitter with an oscilloscope. Figure 8 shows the optical spectrum of the combined waveform, and the eye diagram of the detected signal in the optical domain. The results illustrate the potential for high-quality, high-bit-rate data transmission over the generated carriers, using advanced modulation formats.

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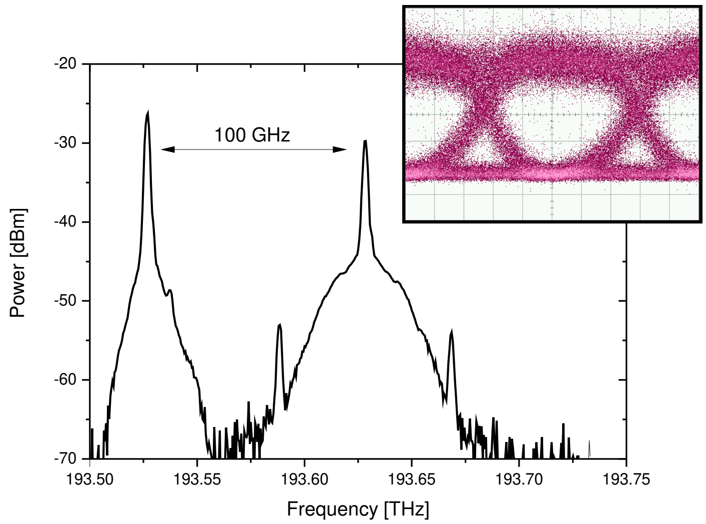

Fig. 8. Optical power spectral density of the two selected tones, following the modulation of one of them by an on-off keying, 40 Gbit/s pseudo-random bit sequence. Inset: eye diagram of the photo-current following down-conversion of the two tones.

6. Discussion and conclusion

Due to the stable amplitude as well as the fixed frequency and phase relations between the comb lines of a mode-locked fiber laser, the electro-optic down-conversion of two of these lines results in a very narrow-linewidth wave with an ultra-low phase noise. These high-quality waves, together with the compact light-weight, reliable and stable setup based on standard components of optical telecommunications makes the method especially attractive in the field of high-bitrate wireless communication.

The arbitrary exclusive selection of two lines is enabled by narrow-band SBS amplification, along with polarization discrimination. Since the frequency of the generated wave is defined by the frequency difference of the two comb lines, a stabilization of the pulse-to-pulse carrier-envelope phase is not necessary. If required, the power of the extracted lines can be enhanced by an additional amplification in an erbium doped fiber amplifier (EDFA).

The frequency stability of the wave crucially depends on the laser repetition rate and the generated frequency. A change of 1 Hz in the repetition rate of our fiber laser, for example, would modify the frequency of a 1 THz waveform by 13.3 kHz. The frequency drift has no influence on the filtering with the DFB laser diodes since the 3 dB bandwidth of SBS is 10 -30 MHz and the lasers are locked by the PDH-module. However, the relatively low repetition rate can be carefully stabilized electrically. Fiber lasers with a very accurate stabilization of the repetition rate are commercially available. Furthermore, with these lasers the repetition rate can be tuned over a broad range, so that the generated frequency can be tuned continuously. For a repetition rate f_{rep} of 80 MHz and a generated wave of 1 THz the number of modes is $m = 12,500$. Thus, a continuous tuning of the wave is possible if the laser repetition rate can be changed by 6.4 kHz, or 0.01% of f_{rep}. If we assume that the repetition rate can be tuned by 1%, continuous tuning is possible from a minimum frequency of 8 GHz up to the spectral bandwidth of the comb. Coarse tuning is possible by the selection of different comb lines and fine tuning by a slight change of the repetition rate.

In conclusion, a method for the tunable generation of high-quality millimeter- and THz-waves with an ultra-narrow linewidth of < 1 Hz and a phase noise of -104 dBc/Hz at an offset of 10 kHz was presented. The wireless transmission of a 1 THz carrier over a distance of 24.5 cm and the modulation of a millimeter-wave carrier by a 40 Gbps signal in the optical domain has been shown as well. The proposed THz generation method can be potentially used for spectroscopy or as a local oscillator in ground- or space-based telescopes. However, the simple setup based on a commercially available, small-footprint fiber laser and standard equipment of optical telecommunications together with the very high quality of the generated waves, makes the method especially attractive for wireless communications with very high bitrates.

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